

GaN-Based Power Transistors for Future Power Electronic Converters

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Abstract—Gallium Nitride (GaN) is increasingly considered a viable semiconductor material in future power electronic converters. The beneficial properties of GaN, being the result of its wide bandgap and the possibility to form heterostructures, make a further optimization of the power conversion possible. Although GaN power devices are still in an early phase, they have already overtaken the silicon counterparts. The expectations are that figures of merits (FOM) of at least an order of magnitude better than those of existing state of the art silicon MOSFETs are feasible in the future. The preference of GaN over other wide bandgap materials like Silicon Carbide (SiC) and Diamond is a matter of 'cost-effective' revolutionary performance. Beside an overview of the properties and advantages of GaN semiconductors, their benefits are demonstrated by a hard switching boost converter that was constructed using E-mode DHFET prototypes on silicon. The low on-resistance ($R_{on} \approx 0.23 \Omega$) and low gate-charges (e.g. $Q_g \approx 15 \text{ nC}$ at $V_{ds} = 200 \text{ V}$) result in minor transistor losses. Together with a proper design of the passives and the use of SiC diodes, high overall efficiencies are reached. Measurements show a high conversion efficiency of 96% ($P_{out} = 106 \text{ W}$, 76 to 142 V at 512 kHz). This is, to our knowledge, the highest efficiency reported for an E-mode GaN DHFET on Si in this frequency range. Allowing higher positive drive voltages can increase the efficiency even further at high frequencies.

I. INTRODUCTION

Power electronic systems play a key role in integrating decentralized production units into the power system as most of the DER (Distributed Energy Resources) use a power electronic converter to interconnect with the utility grid [1]. To maintain and increase the further spread of DER it is important to decrease the cost and at the same time improve the efficiency and reliability of these systems.

In recent years power electronic converters experienced only evolutionary improvements, mostly on the circuit- and topology-side [2]. These improvements often come with an increased complexity and a decreased reliability of the converters. From the components' side of view, the widely used silicon MOSFET power devices are approaching their physical limits in performance, resulting in a saturating 'component related' converter improvement [3]. In addition cost of advancements has increased strongly. However, with the recent

introduction of the wide bandgap power devices revolutionary improvement opportunities rise, enabling a significantly improved performance of future power electronic converters. Especially GaN-based power electronic devices have been recognized to be an outstanding replacement candidate for the currently used silicon devices in power electronic converters [3], [4], [5]. It is expected that figures-of-merit (FOM) of at least an order of magnitude better than existing state of the art silicon MOSFETs can be delivered, enabling dramatic reductions in energy consumption in end applications [3]. The combination of a low on-resistance and low gate charges of the GaN-devices tremendously reduces the losses and permits higher switching frequencies to be applied, resulting in more compact power converters. Moreover it has been shown that these materials can be grown onto large diameter Si substrates [6], which is of course a major cost advantage, especially comparing to other wide-bandgap materials such as SiC.

This paper presents an overview of the advantages of GaN-based power transistors and how they can contribute to the improvement of power electronic energy conversions. Results of measurements on a GaN-based hard-switching boost converter are presented proving the benefit of GaN HFET devices concerning converter efficiency and circuit compactness. A loss distribution graph shows the location of the several converter losses. The practical implementation requires not only dedicated gate drive circuitry, but also a well thought power circuit design in order to deal with parasitic affects, eddy current losses, inductor air gap influences, ...

II. GAN AS A SEMICONDUCTOR MATERIAL

A. Wide bandgap materials: advantages

Gallium Nitride (GaN) belongs to the group of the 'wide bandgap' semiconductor materials, being defined as materials with a bandgap (forbidden energy zone) greater than 1.7 eV. Today's primary used silicon semiconductors only have a bandgap of 1.12 eV [4]. A wide bandgap comes with several advantages, resulting in an improved performance of the power devices using these materials. It translates for example into smaller intrinsic carrier densities than in silicon at the same temperature [4], [7]. This means that devices made of these materials can be used at higher temperatures than silicon devices. Experiments with GaN transistors have proved the

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TABLE I
PROPERTIES OF IMPORTANT SEMICONDUCTOR MATERIALS WITH A POTENTIAL FOR POWER DEVICES

Property	Unit	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap	eV	1.12	1.43	3.03	3.26	3.45	5.45
Dielectric constant (relative)		11.9	13.1	9.66	10.1	9	5.5
Electric breakdown field	kV/cm	300	455	2500	2200	2000	10000
Electron mobility	cm ² /Vs	1500	8500	500	1000	1000-2000 ¹	2200
Hole mobility	cm ² /Vs	600	400	101	115	850	850
Thermal conductivity	W/cmK	1.5	0.46	4.9	4.9	1.3	22
Saturated electron drift velocity	10 ⁷ cm/s	1	1	2	2	2.2	2.7

proper operation at a temperature of 300 °C [7]. Even an operation at 1000 °C in vacuum was demonstrated with GaN-based FETs [8]. Silicon transistors however stop working at temperatures higher than 140 – 150 °C [4], [7]. Beside the high temperatures, higher mobilities can be achieved, meaning that the specific 'on'-resistance ($R_{on,spec}$) of devices made with these materials is smaller than that of the silicon counterparts. Also the critical electric field strength is higher, resulting in a higher breakdown voltage. Finally, the thermal conductivity of these materials is often larger than that of silicon, facilitating device cooling [7], [9]. Table I shows the mentioned properties for the most important semiconductor materials with a potential for power electronic devices.

B. Why Gallium Nitride?

The reason for putting the emphasis on GaN is that it, in contrast with other wide bandgap materials like Silicon Carbide (SiC), Diamond or Gallium Arsenide² (GaAs), can deliver a cost-effective revolutionary performance. SiC and Diamond for example suffer from a intrinsic cost structure of the material and a limited quality material supply [3]. Additionally these technologies are not scalable to large wafer sizes. In contrast, high quality GaN transistors can be grown onto large diameter Si substrates, being a major cost advantage [6]. This is the result of recent improvements in GaN-on-silicon epitaxial processes and device fabrication. The use of this kind of hetero-epitaxial films is required as bulk GaN substrates are high priced. In the past the use of silicon substrates for GaN epitaxy was difficult because of the defects and deformations due to the intrinsic mismatch in lattice constants and thermal expansion coefficients [3], problems that now have been solved. This allows volume deposition of GaN-based material on low cost silicon wafers, costing about 100 times less than deposition on SiC [3].

C. The AlGaN/GaN-based HFETs (Heterostructure Field Effect Transistors)

Gallium Nitride (GaN) is a III-nitride material³, having the advantage that it can be used to form heterostructures [4].

¹This quantity is the result of the AlGaN/GaN heterostructure and not of the intrinsic properties of GaN [4].

²Although the bandgap of GaAs is smaller than 1.7 eV, it is often still considered as a wide bandgap material

³III-nitrides are compounds of elements from column three of the periodic table of elements with nitrogen. Examples are: AlN, InN, GaN.

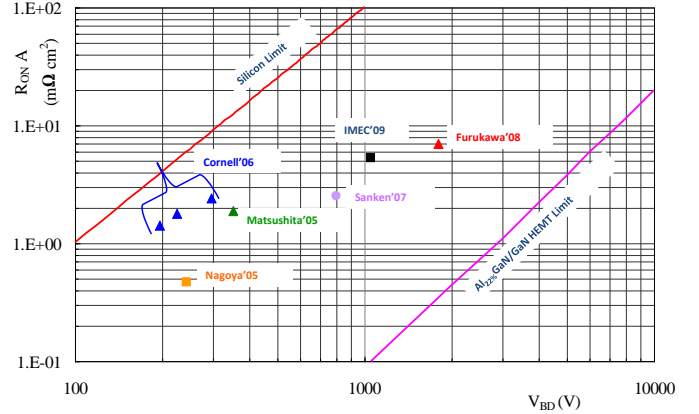


Fig. 1. Specific on-resistance ($R_{on,spec}$) for the different GaN-based power devices found in literature. GaN devices have still a significant grow margin however they already overtook the silicon opponents.

The most famous is the AlGaN/GaN heterostructure. In this structure, a two-dimensional electron gas (2DEG) is formed at the interface, having a high mobility and large carrier concentration. The 2DEG is the result of the spontaneous electrical polarization in GaN and AlGaN and results in low specific on-resistances and high possible switching speeds. Fig. 1 shows the specific on-resistance ($R_{on,spec}$) for the different GaN devices found in literature. The lines represent the theoretical material limits. As Si has evolved towards its limits, GaN has still a significant grow margin. However, despite its immature technology, GaN has already overtaken silicon.

Due to the high mobility and large carrier concentration of the 2DEG channel, the saturation currents can be high and together with the intrinsic high breakdown voltage of the GaN wide bandgap material (3.49 eV bandgap and 3 MV/cm critical electric field) this results in a high power density, being an advantage for power applications. This is also why the gate-charges (Q_g = total gate charge and Q_{gd} = gate-drain charge), needed to switch the devices, are small compared to those of silicon devices of similar power. Converters' switching loss is proportional to Q_{gd} . The bandgap of Gallium Nitride is so large that the material is transparent.

The AlGaN/GaN-based HFETs are field effect transistors (FET). A voltage applied to the gate induces an electrical field. This field controls the flow of charges between source and

drain. In contrast to a conventional silicon FET, the channel of electrons is present without applying a voltage to the gate. By applying a negative voltage to the gate, the channel is pinched off and the transistor is in its off-state. This makes an AlGaN/GaN-based HFET a 'normally on' device instead of a 'normally off' in the case of a silicon FET. This requires a dedicated gate drive circuit.

D. Dynamic on-resistance

One of the biggest concerns when using GaN-based HFETs as a power switch is the possible increase of the 'dynamic' on-resistance ($R_{on,dyn}$) when applying high voltage swings to the drain [10]. This effect, having a direct impact on the conduction losses of the circuit, is often called 'drain current dispersion' and it can be explained by charge trapping at the surface or in the bulk of the III-nitride heterostructure. The trapped charge acts as a virtual gate and depletes the two-dimensional electron channel, resulting in a decreased drain current and an increase of the on-resistance. Effective passivation of the device top surface and optimized field plate structures can reduce these trapping effects.

E. Figure Of Merit (FOM)

The figure of merit (FOM) of a power transistor is a quality number resulting from the multiplication of several device related quantities that are of primary interest for power electronic applications [10], [11]. It makes a comparison between different devices possible. There are several ways to define the FOM, dependently on the objectives. When one is only interested in performance and efficiency, the two quantities of interest are the on-resistance (R_{on}) and the gate-drain charge (Q_{gd} , sometimes also the total gate charge Q_g), which are, as already explained in the previous sections, in the case of GaN transistors superior to those of silicon transistors. R_{on} has a direct impact on the conduction losses of the converter while Q_{gd} is often used in discussions concerning switching speed and driver design [10], [11]. The smaller Q_{gd} , the faster the switching and the lower the switching losses. When multiplying Q_{gd} with R_{on} , a first 'performance' figure of merit (1) is obtained, being particular of interest for engineers and academic people. Fig. 2 shows the 'performance' figure of merit for today's state of the art commercially available silicon transistors and the predicted FOM of future wide bandgap devices. The latter is expected to be an order of magnitude better than that of the silicon transistors [3]. The first generation GaN devices (≤ 200 V), now being on the market [12], already transcend the performance of the state of the art silicon transistors and have still much room to evolve. For manufacturers and customers, cost is often a third quantity that needs to be included, resulting in a 'performance-cost' figure of merit (2). This can further be extended by a third 'performance-cost-density' figure of merit (3) when also the density of the power devices comes into play [13]. As already explained, the two latter quantities (cost and density) also play

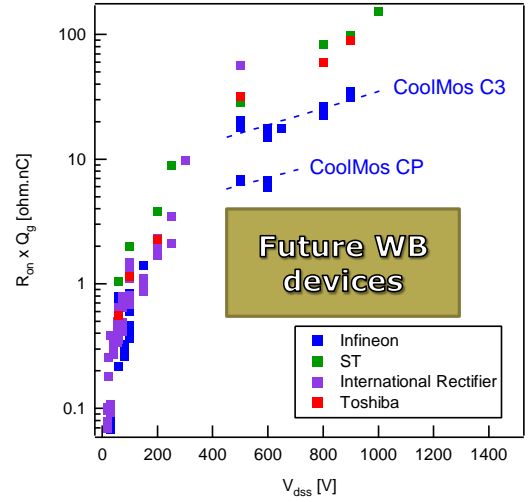


Fig. 2. 'Performance' figure of merit (FOM_p) for different commercially available transistors and the expectation for future wide bandgap transistors.

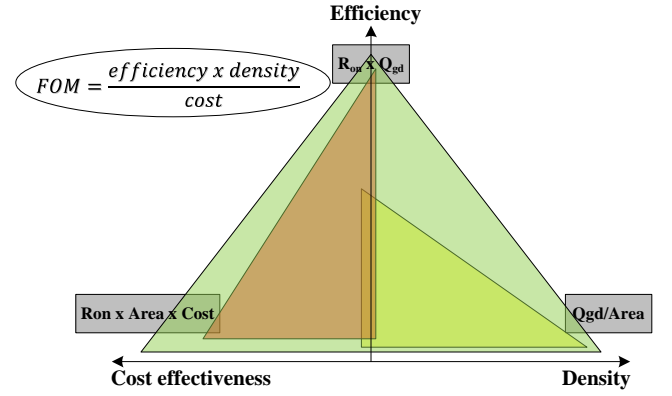


Fig. 3. Trade-off between the key quantities in the 'performance-cost-density' figure of merit ($FOM_{p,c,d}$). (source: [13])

in favor of GaN, resulting in a superior $FOM_{p,c,d}$.

$$FOM_p = R_{on} \times Q_{gd} \quad (1)$$

$$FOM_{p,c} = R_{on} \times Q_{gd} \times Cost \quad (2)$$

$$FOM_{p,c,d} = \frac{Efficiency \times Density}{Cost} \quad (3)$$

As seen in fig. 3, there is always a trade-off between each quantity that determines the FOM ('Area' = transistors' device area). If the inner triangles represent this trade-off for the present used silicon power devices, the outer triangle shows how the future GaN-based devices could extend and improve this trade-off area [13].

III. IMPACT OF GAN ON CONVERTER PERFORMANCE

In this section the influence of GaN based transistors on the performance of a real converter is studied. A hard switching boost topology is chosen as it is often used for power-factor-correction (PFC) front ends and as the basic building block of half bridges, making it a good tool to demonstrate the advantages of GaN based transistors in a power electronic

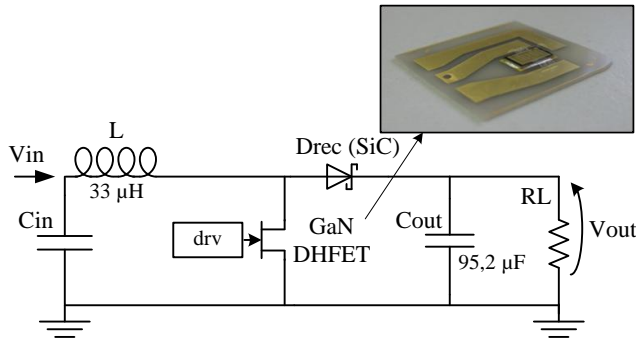


Fig. 4. Boost converter circuit with flexible high-frequency gate drive circuit (up to 2 MHz) to test the E-mode GaN DHFETs. (upper inset) GaN E-mode DHFET mounted on an AlN carrier substrate.

converter. The emphasis is on converter efficiency and switching frequency ($\hat{=}$ compactness).

A. Test circuit

Fig. 4 shows the main power circuit diagram of the hard switching boost converter. Effort was put in making the power circuit extremely compact, reducing the parasitic influences to a minimum. The inductor, for example, is a in house developed planar inductor. State of the art SiC diodes were used as rectifier elements and special attention was paid to the design of the passive components aiming for the highest possible efficiency. The SiC diodes are 6 A Schottky diodes, offering superior switching characteristics with very low recovery current, minimizing their impact on efficiency and operation. The gate drive circuit can reach frequencies up to 2 MHz and has an adjustable voltage range, making it possible to deliver negative voltages.

B. Tested transistors: GaN enhancement mode DHFET devices

Nowadays more attention goes to normally off (Enhancement Mode (E-mode)) GaN transistors due to their inherent safety [14] [15]. There are several ways to transform the inherently normally on (Depletion Mode) AlGaIn/GaN devices into normally off devices [15] [16]. The transistors we use in our test setup are large (57.6 mm total gate width and 1.5 μ m total gate length) enhancement mode AlGaIn/GaN/AlGaIn DHFETs (Double Heterojunction Field Effect Transistors) grown on Si<111> (see Fig. 5) [15]. These lateral power devices are fabricated starting from a $\text{Si}_3\text{N}_4/\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}/\text{GaN}/\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}$ MOCVD grown heterostructure on a Si<111> substrate [6]. In order to obtain an E-mode device ($V_T > 0$), the $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ barrier thickness is scaled down to a thickness of 5 nm and at the same time the in-situ grown Si_3N_4 is selectively removed under the gate. To integrate the GaN DHFETs into power electronic circuits, the dies are packaged onto an AlN ceramic carrier (see inset of Fig. 4), acting as a heat spreader. Fig. 6 shows the dynamic on resistance ($R_{on,dyn}$) and gate charge values (Q_g) of the GaN transistor as they were measured using the boost converter setup. The dynamic on-resistance is around 0.23 Ω and only shows a very minor increase with increasing

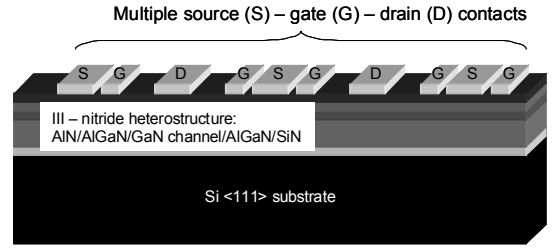


Fig. 5. Simplified cross-section of the GaN DHFET device. The power device is a lateral FET device, having multiple source (S) / gate (G) / drain (D) contacts on top of the III-nitride heterostructure.

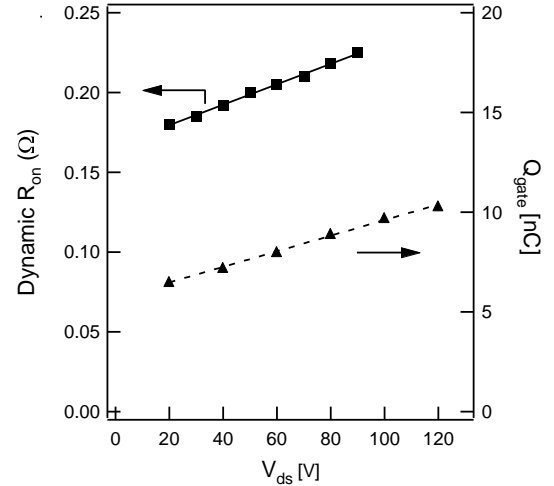


Fig. 6. Dynamic on-resistance ($R_{on,dyn}$) and total gate charge (Q_g) of a GaN DHFET ($W_g = 57.6$ mm), measured using the boost converter shown in Fig. 4.

off-state drain voltage ($V_{ds,off}$), proving the absence of the surface or bulk electron trapping in the device. A total gate charge value of 10 nC is obtained at $V_{ds,off} = 120$ V. These low quantities result in a excellent 'performance' figure of merit ($FOM_p = 2.3 \Omega nC$) and low transistor losses (conduction respectively switching).

C. Results

Efficiency

The converter was tested at several output voltages, frequencies and output power ranges, while keeping the duty-cycle constant at approximately 50%. Fig. 7 shows the efficiency measurement (solid line) at 140 V output voltage and 100 W output power in a frequency range from 512 to 845 kHz. The efficiency decreases, as expected, linearly with frequency from 96% at 512 kHz to 93.7% at 845 kHz. To our knowledge, these are the highest efficiencies reported for an enhancement mode GaN DHFET on a Si substrate in these operating conditions and frequency ranges [14]. These high frequencies allow a compact converter design as the inductance (L) of the inductor can be kept small ($L = 33 \mu$ H in our case). When decreasing the frequency or working

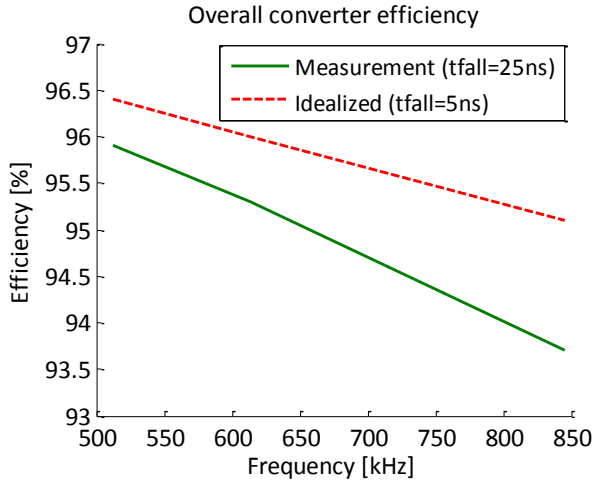


Fig. 7. Converter efficiency measurement at $P_{out} = 100$ W and $V_{out} = 140$ V as a function of the switching frequency.

at higher voltages, even higher efficiencies can be reached. Efficiencies are measured using a Voltech PM6000 Power Analyzer and include input filter, output filter and wiring losses.

Distribution of the converter losses

The distribution of the converter losses (see Fig. 8) shows that a major amount of the losses are switching related. According to the current and voltage profiles shown in Fig. 9, the switching losses can be described by the following equations:

$$P_{sw} = P_{sw,on} + P_{sw,off} \quad (4)$$

$$where \quad P_{sw,on} = \frac{I_d \cdot V_{ds,off}}{2} \cdot \frac{t_2 + t_3}{T} \quad (5)$$

$$P_{sw,off} = \frac{I_d \cdot V_{ds,off}}{2} \cdot \frac{t_b + t_c}{T} \quad (6)$$

I_d is the drain current of the GaN-transistor and $V_{ds,off}$ its off-state drain-source voltage. Most of the switching losses are situated in time-intervals t_3 and t_b . During these intervals the gate-drain capacitance (C_{rss}) is charged/uncharged until a $V_{ds,off}$ voltage change across its terminals is reached. Measurements show that the fall time (t_3) of the drain to source voltage is 25 ns (at 120 V), as opposed to 4.6 ns for its rise time (t_b). This results in a relatively high turn-on switching loss. Fig. 8 indicates the impact of this big fall time (t_3) on the overall converter efficiency. The dashed line in Fig. 7 shows the expected efficiency when t_3 would be as small as t_b . This increase in efficiency is relatively bigger at higher frequencies. Reaching a low fall time ($t_3 \approx 5$ ns) is just a matter of allowing higher positive drive voltages as this increases the positive gate voltage-swing and thus the gate charging current.

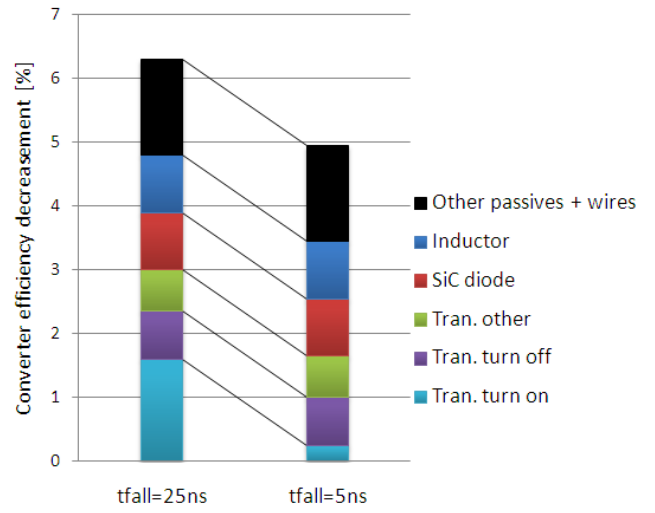


Fig. 8. Distribution of the converter losses. $P_{out} = 100$ W, $V_{out} = 140$ V and $f = 845$ kHz.

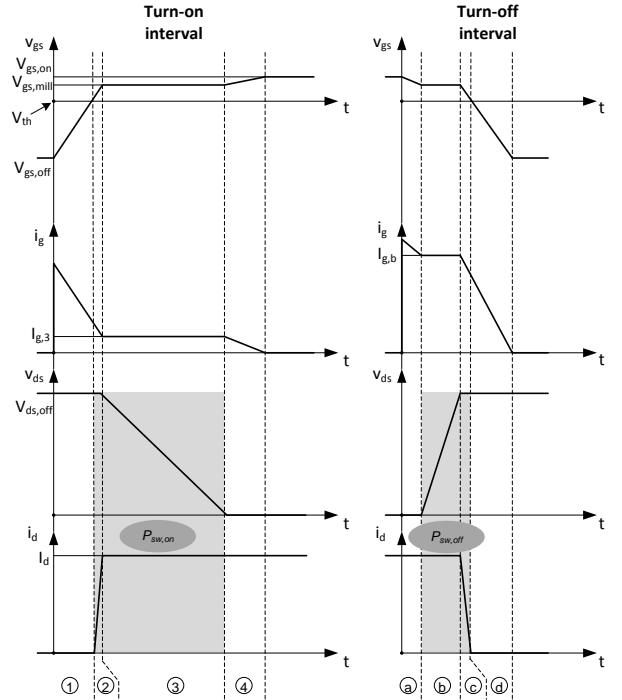


Fig. 9. GaN DHFET turn-on (left) and turn-off (right) intervals.

IV. CONCLUSION

Silicon as a semiconductor material for power devices is gradually reaching its performance limits while Gallium Nitride (GaN) is increasingly considered as a viable replacement candidate that can represent a revolution in future converter performance. An overview of the properties and advantages of wide bandgap semiconductors and specifically of GaN was given. GaN is preferred over other wide bandgap materials like SiC, GaAs and Diamond as it can deliver a 'cost effective'

revolutionary performance. Nevertheless GaN power devices are still in an early development phase, they have already overtaken the state of the art silicon based power devices and it is expected that 'performance' figures of merit of an order of magnitude better than those of their silicon counterparts can be delivered in the future. For proving the benefits of GaN based power devices in a real converter, a high-frequency, hard-switching boost converter was constructed, emphasizing on efficiency and frequency ($\hat{=}$ compactness). The used transistors are E-mode AlGaIn/GaN/AlGaIn double-heterostructure FETs as these have a great interest. The low dynamic on-resistance and low gate charges of the components result in low transistor losses, enabling very high switching frequencies and a compact converter design. A high power efficiency of 96% was reached at a frequency of 512 kHz at 100W output power. This is, to our knowledge, the highest efficiency reported for an E-mode GaN DHFET on Si in this frequency range. Allowing higher positive gate drive voltages would even increase this efficiency.

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